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# Final Report

## Terrestrial Solar Cell Module Automated Array Assembly Task 4

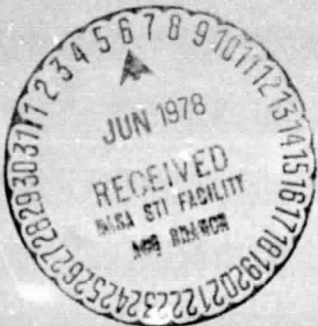
Prepared by

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20554 Plummer Street  
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for

Jet Propulsion Laboratory  
California Institute  
of Technology

January 1978



N78-23565

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16752

G3/44

(NASA-CR-156982) TERRESTRIAL SOLAR CELL  
MODULE AUTOMATED ARRAY ASSEMBLY, TASK 4  
Final Report (ARCO Solar, Inc., Chatsworth,  
Calif.) 27 P HC A03/MF A01 CSCI 10A

FINAL REPORT

TERRESTRIAL SOLAR CELL MODULE  
AUTOMATED ARRAY ASSEMBLY - TASK 4

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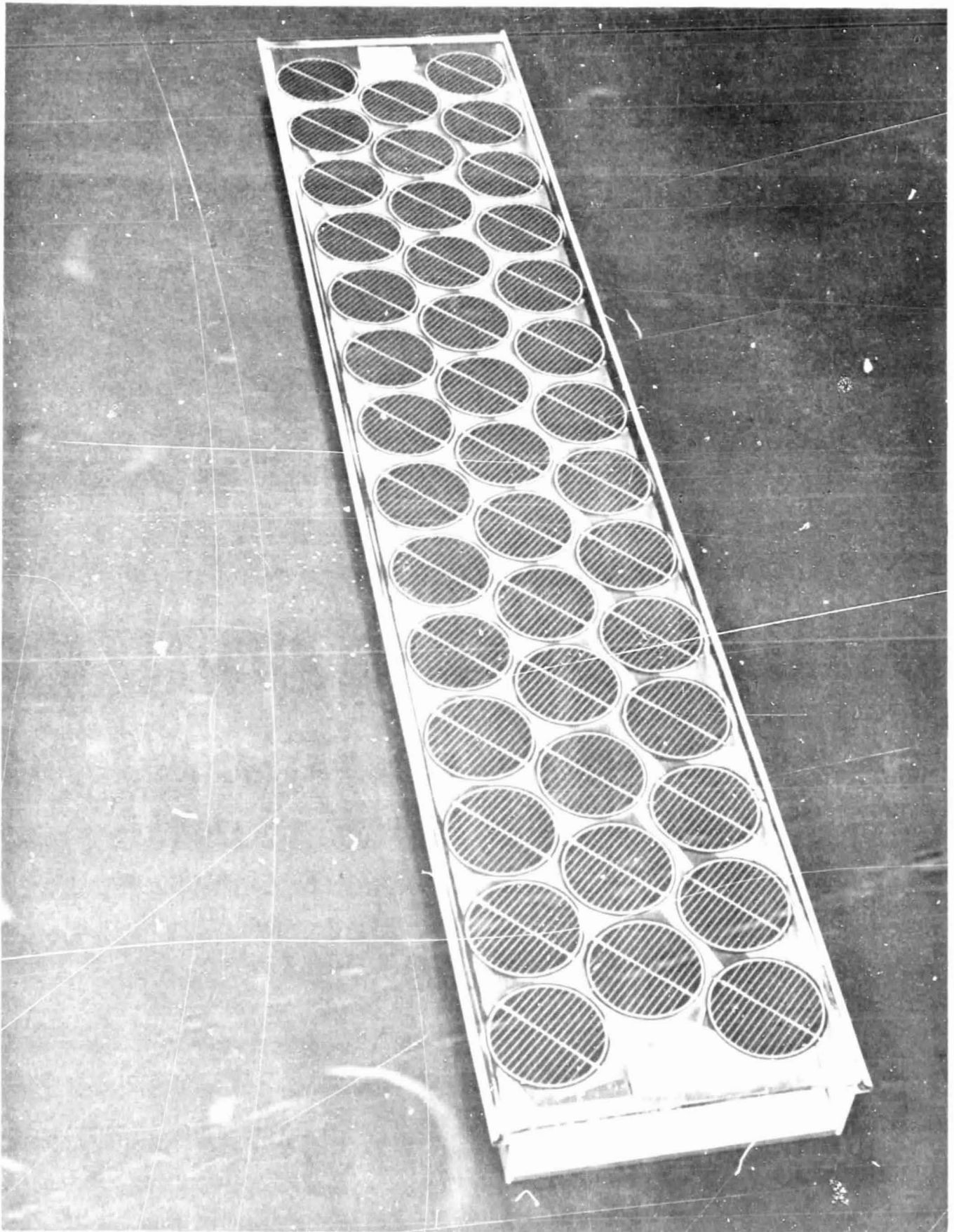
January 1978

DRL Item No. 003  
DRD No. MA 006

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TERRESTRIAL SOLAR MODULE  
ICD 10699  
ARCO SOLAR, INC.



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## 1.0

### INTRODUCTION

In 1976, Solar Technology International, ARCO Solar's (ASI) predecessor company, began experimental construction of solar modules using glass and polyvinyl butyral. Exploratory use of these materials was based on the excellent prior field experience with these materials in automobile windshields. Tests indicated that adhesion of the PVB to silicon, glass, and several metals was excellent.

During 1977, ASI's primary goal during this Task IV LSSA development contract was to work on an aluminum paste P+ back contact and to establish a module design and associated production process sequence capable of passing preproduction qualification testing at JPL.

This final report describes the processes and the module design which were developed by ASI, approved by JPL, and successfully tested in accordance with JPL environmental test specification No. 5-342-1-B. Design considerations related to performance characteristics, process development efforts, fabrication techniques, and actual test results are discussed.

## 2.0 SUMMARY/CONCLUSIONS

### 2.1 SUMMARY

ASI's objective on this program was to establish a cost effective design and manufacturing process that would produce solar cell modules capable of meeting the JPL qualification test criteria. In addition, emphasis was placed on the development of an aluminum paste back contact process.

The basic design was that which had been implemented into production at ASI in early 1977. It consisted of a glass/polyvinyl butyral/Mylar laminate mounted in either aluminum or stainless steel frames. To achieve a satisfactory power output margin, we expanded our production 36 three-inch solar cell design to 41 cells interconnected with ASI's standard dual redundant contacts.

Aluminum paste as a back contact has both performance and cost advantages which warranted its production evaluation. The major effort involved firing the aluminum in a large belt furnace. Prior to this time, cells were successfully fired by hand in diffusion tube type furnaces. When printed aluminum was belt fired in small lots, i.e., less than 200 wafers, acceptable cells were produced. However, when implemented into production, i.e., 1,000 wafer lots, resistance increased a factor of two. Based on this result, production of the aluminum back contact in the existing muffle type furnace was stopped, awaiting installation of a new infrared furnace.

A total of twelve modules were delivered to JPL for qualification testing. Six modules were assembled using ASI standard silver back contacts mounted in stainless steel frames and six contained aluminum back contact cells from the substandard 1,000 cell run mounted in aluminum frames. All modules successfully passed the qualification criteria.

## 2.2 CONCLUSIONS

- 2.2.1 The glass/PVB/Mylar laminate is a superior moisture resistant assembly. When assembled into an aluminum frame, the structural characteristics exceed terrestrial application needs. To further the cost objectives of the LSSA Program, alternate front and back surface materials warrant evaluation.
- 2.2 The use of aluminum paste as a silicon solar cell back contact has the potential advantage of low resistance at low temperature firing and a highly doped P+ region contributing to improved cell output. Further, the aluminum has a substantial cost advantage when compared to silver paste. It is, however, necessary to perform further development to establish a process which is compatible with volume production.

### 3.0

#### MODULE DESIGN

A proposed module design was established at the outset of this program, consisting of 41 three-inch diameter round silicon solar cells interconnected in series with redundant contacts and encapsulated within glass/polyvinyl butyral/Mylar laminate with polysulfide edge sealant and a lightweight metal support structure. A plan view and cross section of the configuration are shown in Figure 1.

This particular laminate represents the adaptation of an existing large volume industrial process, namely the glass-PVB-glass lamination used for automobile windshields and safety glass, to a solar energy application. Mylar is substituted for the second glass layer for the practical reasons of weight reduction and conformance to the encapsulated parts.

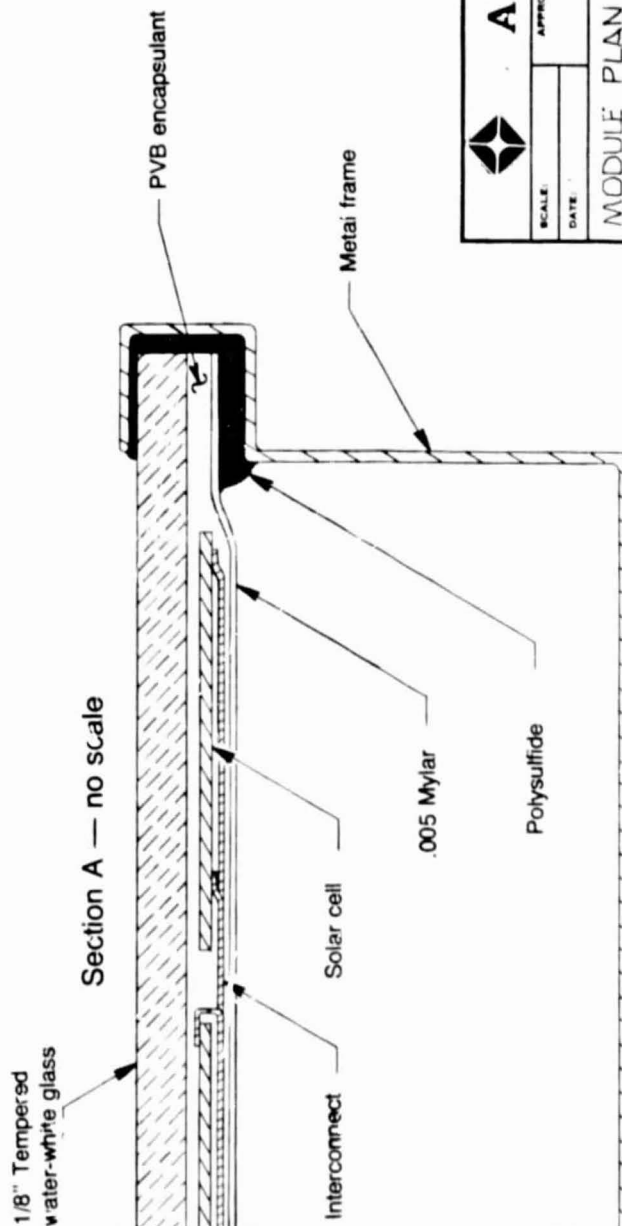
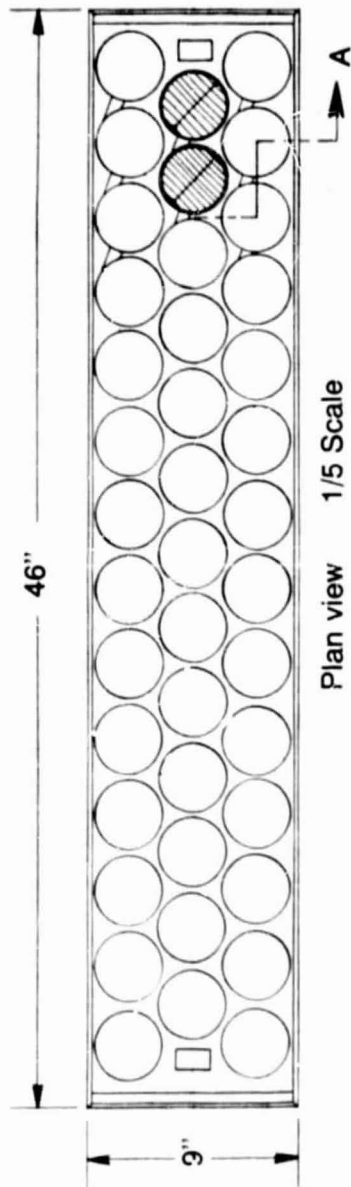
#### Transparent Front Window

Glass has emerged as an especially desirable front surface material for solar power modules because of its inherent weatherability, cleanability, and resistance to moisture penetration. It is available in large quantities of any desired size and thickness.

#### Types of Glass

Three general types of glass were considered for present purposes: float, low iron, and water white. Each of these types is characterized by differing iron contents which in turn affects their optical clarity. Water white glass, with the lowest iron content, is very nearly crystal clear, having a typical transmission exceeding 90% over the





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MODULE PLAN VIEW & CROSS SECTION

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wavelength range of .4 to 1.2 microns. Float glass, on the other hand, has a relatively high iron content and its transmissivity falls off rapidly in the near-infrared wavelength region where silicon solar cells exhibit their peak spectral response. Cell output suffers accordingly. Measured differences exceeding 10% in output power were recorded for test samples using each of these types of glass. Low iron glass represents an intermediate alternative; however, a typical loss in output power of equivalent to 5% could be expected compared to water white glass.

Not surprisingly, the cost of these glass types is increasingly higher for the more desirable cases. Nevertheless, water white glass was chosen for present purposes since the value of the differential electrical output thus obtained far outweighs the increased cost of glass.

#### Resilient Bonding Material

Several formulations of polyvinyl butyral with proprietary additives, each tailored to some specific application, are available in large quantities from Monsanto. Discussions with the manufacturer led to our choice of SAFLEX SR-11, a clear architectural interlayer, as being best suited for present purposes. This product is supplied as .015" thick sheet in 750' rolls of any desired width. One surface is skived (grooved) to permit air flow during vacuum evaporation. SR-11 does require cold storage (40°F, 65% R.H.) to prevent self-fusion (blocking), but no additional preparation is necessary.

Rear Moisture and Mechanical Barrier

Mylar is a tough, durable film with low water vapor transmissivity. Thus it provides mechanical and environmental protection when used as a back surface barrier. Polyester films of similar characteristics are available in .005" thickness for as little as 6-1/2¢/sq.ft.

The proposed module design was implemented at ASI using many existing commercial production process procedures. The glass/PVB/Mylar lamination and aluminum paste cell contacting which represents a major part of this contract effort, are discussed in the following sections.

#### Lamination

Glass/PVB/glass laminates are routinely fabricated by laying these materials together and enclosing the assembly in a suitable vacuum bag such as nylon. As air is evacuated to an adequate level (less than 500 millitorr) the bag deflates and conforms to the assembly pressing it together with a uniform pressure equivalent to 15 PSI on all surfaces. Then under pressure and free of entrapped air, the assembly is heated to a temperature (e.g. 265°F) until the PVB has flowed together forming a void free interlayer. For glass/PVB/glass lamination, the assembly is then placed in an autoclave for a higher pressure/heat cycle which produces an optimum glass/PVB bond, a bond reported by Monsanto to be stronger than the shear strength of the glass itself.

Two fundamental problems were encountered in trying to adapt this process directly to module fabrication. First, a back surface glass layer is not able to conform into the depressions between cells, thus leaving large voids in these areas. Second, during a high pressure autoclave cycle the lateral movement of material exerts high forces on the cells, breaking interconnects and cells.

To overcome the first problem, a flexible Mylar film was substituted for the back surface glass layer. This "half laminate" configuration has the further advantage of significant weight reduction. The properties of Mylar are considered adequate for back surface protection as discussed elsewhere in this report.

### Bond Strength

The most cost effective way to eliminate cell and interconnect damage is to simply eliminate the secondary autoclave cycle at the expense of less than maximum bond strength. This was, in fact, the approach taken as development work proceeded to establish a practical lamination procedure. Early test samples, bonded in nylon bags on a hot plate, exhibited glass/PVB bond strengths equivalent to 3-4 lb/in width (1" width test strips pulled at 45°). Similar values were obtained routinely for any time-temperature cycle which produced void free interlayers. Further data, accumulated over a period of several months, substantiated this bond strength range as being typical for a non-autoclave process. To put this result into perspective, it requires a substantial physical effort to separate two large sheets of these materials after bonding.

### Mylar Treatment

By comparison, early Mylar/PVB bond strengths were quite low, less than .5 lb/1" width, and the Mylar peeled off quite easily. Longer, hotter heat cycles offered no improvement. Discussions with the manufacturer (DuPont) led to the realization that Mylar is a very non-active



material that requires a surface treatment to improve bondability, as in the case of Mylar/adhesive/copper bonding, or printability, where inks are applied to Mylar. Suggested methods included exposure to Toluene vapor or hot sodium hydroxide, surface abrasion, or corona discharge. The last alternative was pursued as being potentially the most practical.

A corona discharge occurs in the air gap between two electrodes when a high voltage radio frequency is applied across them. By passing a Mylar film through this volume of ionized species, a change in the surface chemistry is produced which improves bondability.

A corona discharge power supply was procured from one of several manufacturers of such equipment, and a Mylar treating station established, capable of continuously treating 5 ft/minute of 12" wide film.

After some initial electrode configuration development and power density adjustments, treated Mylar-PVB bond strengths approaching 3 lb/l" width were routinely obtained by vacuum laminating as discussed above.

It is noteworthy that corona discharge treating is a clean, dry process, that is easily implemented and compatible with large volume production. It does produce a noticeable level of ozone which must be vented from the work area.

The vacuum bag technique is certainly practical for large area and irregularly shaped items such as automobile

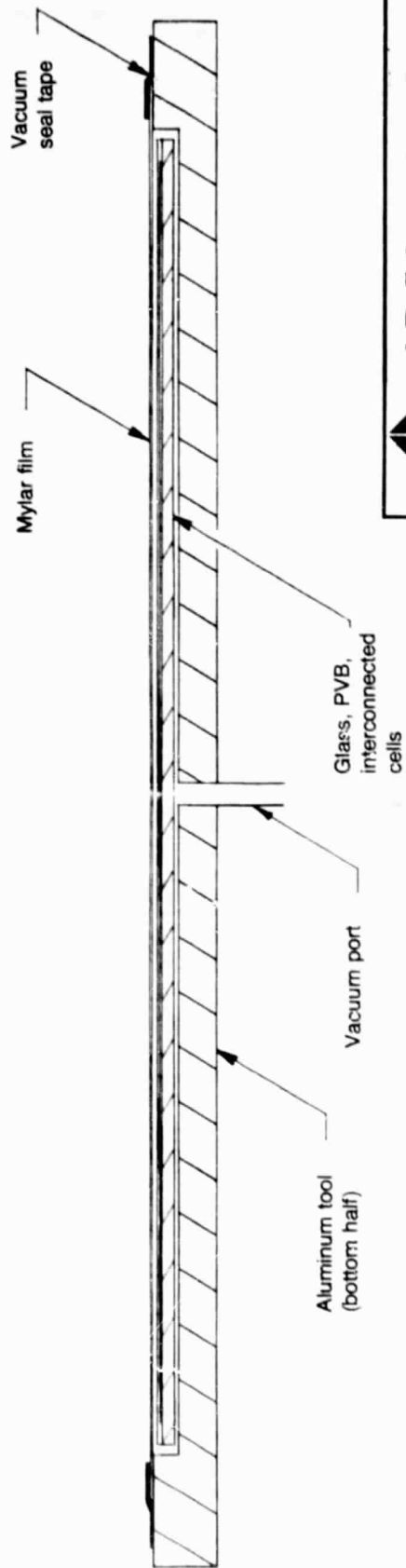
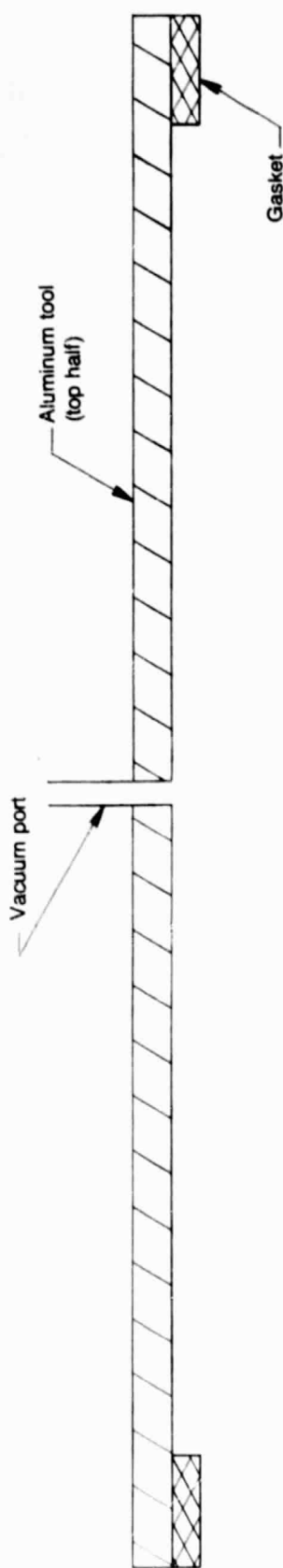
windshields. However, for present purposes, a more efficient technique was developed by employing a reusable metal vacuum tool and the Mylar film as the conformable bag. In this manner the vacuum bag material becomes a part of the completed module, except for a small amount of excess around the perimeter.

The vacuum tooling configuration used to laminate the 12 delivered modules is shown in cross section in Figure 2 as loaded and ready for pumpdown.

The module assembly is first placed in the bottom tool half, then the treated Mylar film is laid over the tool and taped to the edge flange to form a vacuum seal. The tool half, with vacuum gasket, is then set in place and top clamped down. The top half vacuum port is then opened, followed by the bottom port.

A key requirement for successful module lamination is the complete removal of air from each layer of material. Although the PVB is skived (grooved) to permit air flow, the conductance of this flow is very low when pressure is applied and the time required for complete evacuation under this condition, as would be the case for a vacuum bag, is excessive, being on the order of 8-10 hours for a part this size (9" x 45-1/2"). The top tool half, or "backing plate," as shown in the figure, eliminates pressure on the Mylar film during pumpdown with reduced cycle times of only 5 to 15 minutes resulting.

The top port is then closed off and the upper vacuum vented. At this point, atmospheric pressure is applied



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to the Mylar film and it presses down on the underlying assembly which is still under vacuum. The top vacuum barrier is then removed and the entire bottom tool is then placed on a large surface area hot plate for an equivalent to 15 minute heat cycle to 270°F which is sufficient to allow the PVB to flow together encapsulating the cells in a void free volume and bonding the various materials together. After cooling, a completed laminate is cut out of the tool and prepared for final assembly. The tape seal and excess Mylar are pulled off the tool and it is ready for another cycle.

#### Aluminum Paste Back Contacts

Aluminum is an especially attractive candidate material for N or P type silicon solar cell back contact metallization because of its low cost, compared to silver, and the fact that it alloys with silicon at a relatively low temperature to form not only a low resistance ohmic contact, but also a highly doped P+ region which can enhance cell output under certain conditions.

Aluminum metallization is conventionally a high vacuum process involving the evaporation of pure metal. However, a low cost and non-vacuum alternative suitable for solar cell processing has been under development for several years. Silk screen printed aluminum paste was first used as a back contact material and P+ dopant source for solar cells in 1975 under NASA Contract No. NAS3-18566. During subsequent development contracts, the baseline process was refined and improved, however, certain process incompatibilities have limited its use in full scale production.

Up to this point, best results, in terms of back contact resistance and P+ back surface field effect, had been obtained using a fritless aluminum paste, air fired a few wafers at a time in a high temperature (800° - 900°C) open tube furnace for very short times, less than one minute. Two reactions occur during firing: first, a portion of the paste fuses with silicon to form a eutectic melt; second, the remaining aluminum nearest the outer surface oxidizes and prevents dissolution into the melt. Other parameters are known to affect the ratio of oxidized to fused aluminum, including paste formulation, printed thickness, printed density, and preheat cycle time/temperature profile.

A high fused aluminum content is desirable since the back contact layer thus formed is thicker and has a lower lateral series resistance. The P+ doping effect is also enhanced in this case.

One further problem inevitably encountered when firing aluminum paste is the conglomeration of molten aluminum due to surface tension effects which create lumps on the back surface. This makes further processing difficult when vacuum hold down is required, such as for silk screen printing front contacts or electrical testing.

With all of these considerations in mind and given a wealth of prior experience, an attempt was made to optimize an aluminum paste process at ASI using existing equipment. At the outset, the decision was made to use a large conveyor belt muffle furnace for firing even though the desired short cycle time previously used could not be simulated.



The furnace in question is 30' long, and running at maximum speed has a time at peak temperature equivalent to 8 minutes. Nevertheless, this furnace is capable of firing in excess of 2,000 wafers/hour in a continuous manner and therefore represents a significant throughput advantage over tube furnace firing a few wafers at a time. Frankly, the probability of obtaining an optimized P+ effect in such a furnace was considered marginal, but for the relatively thick, low resistivity cells being processed, this did not seem like a major disadvantage. Initial experiments indicated that adequate low back contact resistance could be obtained and, in fact, several preliminary small batches of cells processed through this furnace had back surface resistances approaching their silver paste counterparts.

Continued experimentation led to furnace settings giving a peak temperature of 730°C. At higher peak temperatures, one small lump of aluminum per wafer would form an alloy into the wafer so that it could not be removed. At the lower temperature the small lump would still form, but could be removed quite easily. Past experience indicated that this lumping effect could be eliminated by a very fast heat up cycle. Constrained by existing furnace capability, the alternate solution of lowering temperature to allow lump removal had to be employed.

Over a period of several months numerous small batches 25-200 wafers were processed with aluminum backs. Resulting contact layer formation was always less than ideal because the low temperature constraint limited silicon fusion. Nevertheless, back contact resistance only slightly

higher than silver paste, .02 ohms vs. .01 ohms, were usually obtained and the decision was made to process full production lots of 1,000 wafers.

A procedure was fixed based on recent experiments and production operators were employed to complete this task. The typical back contact resistance thus obtained was equivalent to .04 ohms, a value much higher than expected. This increased series resistance which produced an average panel degradation of 12% as discussed later, is attributed to some variable or variables not adequately controlled by the existing procedure. Based on these units, the aluminum contact was not implemented into ASI commercial production.

After firing, this aluminum process requires a number of subsequent operations not common to the conventional silver paste process, namely oxidized powder removal and silver paste solder and formation. These steps are not material or labor intensive and contribute only an incremental cost per wafer of equivalent to \$.05.

The aluminum paste used during this program is especially cost effective. The formulation consists of 70% aluminum powder, 28% pine oil, and 2% ethyl cellulose and when mixed in-house, costs approximately \$.01 per wafer in small quantity, as compared to the \$.12/wafer for the for the lowest cost commercial silver paste DuPont 7095. This potential savings of \$.11/wafer demands the continued consideration of aluminum paste.

### Interconnection

Bonding interconnects to aluminum, or in this case Al + Si, presents a problem in conjunction with conventional soldering techniques. Several solutions were considered for this program: nickel plating, conductive epoxy, or silver paste solder pads. The last alternative was chosen because of the masking problems associated with preferential plating and reported poor results with epoxies. Silver paste pads have been used previously and, in fact, have satisfactorily passed pull strength testing after humidity exposure without encapsulation. This technique proved to be satisfactory, but did require an additional printing cycle.

As a part of the ASI independent research and development program, ASI has experimented with ultrasonic soldering and special solder alloy and successfully soldered directly to aluminum. This technique will eliminate the extra process steps presently required.

ASI has recently installed an infrared conveyor belt furnace capable of 1-2 minute cycle times and peak temperatures in excess of 800°C. Experiments firing aluminum paste in this type of furnace indicates that optimum results, i.e., that contact layers with low resistance and no lumps, can be obtained.

It is recommended that additional work be conducted in Task IV ASI contracts to investigate the use of this new equipment. ASI considers the successful production of printed aluminum back contacts with P+ effect to be important to meeting the LSSA cost goals.

## ALUMINUM PASTE CONTACT METALLIZATION

### PROCESS STEP DESCRIPTION

#### Back Contact Formation:

1. Cassettes are loaded and dried
2. Material procurement
3. Paste preparation
4. Printer setup, oven unload warmup, furnace warmup
5. Print aluminum paste
6. Dry
7. Fire
8. Load
9. Ultrasonic tank warmup to equivalent of 60°C detergent, etc.
10. Dump into quartz
11. Immerse until clean
12. Dump back to plastic
13. Rinse in city water
14. Hf 15 sec. 10% Hf
15. Rinse in city water
16. Spin dry
17. Printer setup, paste
18. Print front grid pattern
19. Dry
20. Load into boats
21. Printer setup and paste
22. Unload and print back pads
23. Dry
24. Fire in muffle furnace
25. Load
26. Unload and print plating resist on back pads
27. Dry
28. Load
29. Hf
30. Rinse
31. Ultrasonic clean Tric and alcohol
32. Spin dry
33. Test



Design considerations related to the module performance characteristics observed during JPL testing are discussed in the following sections.

#### Electrical Output

Based on typical electrical characteristics of ASI commercial production modules with Ag paste contacted cells and assuming a minimum 5% improvement in short circuit current with the proposed water-white glass/PVB encapsulation, it was anticipated that the electrical requirements and surface area constraints imposed by this contract could conveniently be satisfied using 9" x 46" modules with 41 conventional production solar cells (3" diameter round) interconnected in series. Equivalent results were predicted for the alternate, where aluminum paste back contacted cells to be fabricated according to procedures developed during this contract, would be used.

The average output power of the six conventional Ag paste contacted cell modules tested at JPL was 22.65 watts ( $100 \text{ mW/cm}^2$  and  $28^\circ\text{C}$ ), and the minimum module output was 22.46 watts. This group clearly satisfies a 20 watt/module and 100 watt/5 module minimum electrical requirement.

The average output power of the six Al paste back contacted cell modules was 20.22 watts. The minimum module output was 19.43 watts, slightly less than the 20 watt design objectives.

### Thermal Cycle

Polyvinyl butyral and polysulfide are both resilient materials throughout a wide temperature range, thus providing needed stress relief during thermal cycling at the interfaces between all of the various system components, including each of the laminate materials, the solar cells, and the metal frame. Further protection is provided by front contact interconnect tabs which loop through 180 degrees to provide stress relief.

Preliminary test samples successfully passed thermal cycle testing (50 cycles from  $-40^{\circ}$  to  $+90^{\circ}\text{C}$ ) and no significant degradation was recorded during equivalent JPL testing of 10 modules (less than 1% in all cases).

### Humidity

The two major surface areas of a glass/PVB/Mylar laminate are highly resistant to moisture penetration. The front glass cover is virtually moisture proof and the .005" thick Mylar film has a low water vapor transmissivity of only .24 g/100 in.<sup>2</sup>/24 hours\*. Within these outer barriers, the .030" thick (path of least resistance) PVB interlayer with extremely low transmissivity adds further protection. Along the edge of the laminate, a small fraction of the total surface area, the exposed PVB is sealed with polysulfide.

Further, the vacuum lamination process being used assures a void free encapsulation, thus eliminating osmotic migration and accumulation of water vapor.

\*ASTM Method E-96

By reducing moisture penetration, this encapsulation system minimizes the potential for galvanic corrosion of cell contacts and interconnects.

These considerations supported a high expectation of successfully passing the JPL humidity test. In fact, the mean degradation of the five Ag contacted modules tested was only .6% and of five Al contacted modules 1.3%.

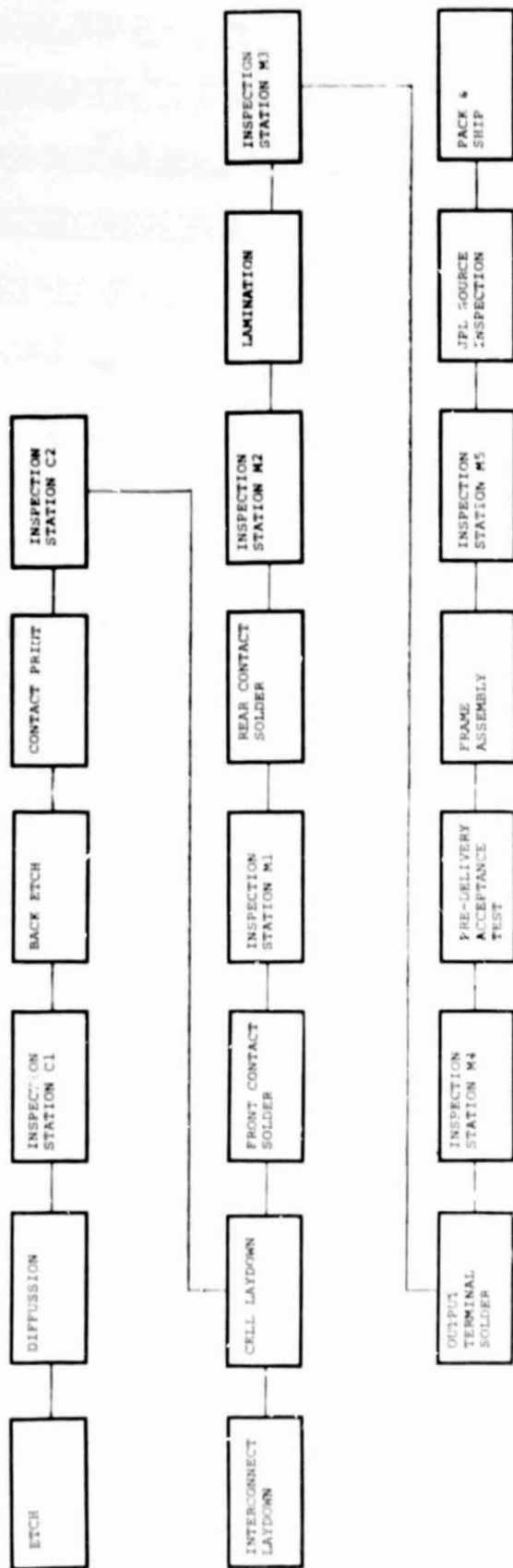
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### FABRICATION

With the exception of the aluminum back contacts, the entire fabrication process utilized in this program is that which had been previously implemented at ASI. The attached flow diagram, Figure 3, reflects the sequence of manufacturing processes.



MANUFACTURING FLOW DIAGRAM  
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TESTING

Preliminary test sample modules were subjected to insulation resistance, high voltage withstanding, thermal cycle, humidity, and mechanical integrity testing, all per JPL specification 5-342-1 Revision B. Satisfactory results were obtained during testing. These tests were performed, for the most part, by Applied Engineering Test Labs.

Each of the 12 modules subsequently delivered to JPL was visually inspected and electrically tested outdoors at ASI to confirm general compliance with contract requirements.

At JPL the modules were visually inspected and electrically tested on their pulse simulator (100 mW/cm<sup>2</sup> and 28°C) before and after thermal cycle, humidity, and mechanical integrity testing. Two modules were held out as controls. The maximum output power and accumulated percent degradation of each module at each test point is given in Table 1 and 2.

The test data provided by JPL cited no significant functional degradation. Five modules, in fact, evidenced improved performance following test. Visual examination following thermal test indicated four Ag contact cells had hairline cracks near the edge of the cell. Three of the cells were in one module and one in another. No other defects were noted. The redundant electrical contacts minimized power loss.

TABLE 1  
ENVIRONMENTAL TEST RESULTS  
AL BACK CONTACT

I.D. No.	Description	Test Point	P max (watts)	$\Delta$ P max (accumulated %)
101936	Al Contacts	I (initial)	19.43	0
		T (thermal)	19.41	-.1
		H (humidity)	18.76	-3.4
		M (mechanical)	18.56	-4.5
101937	Al Contacts	Control @ I	20.61	0
		Control @ T	20.48	-.6
		Control @ H	20.34	-1.3
		Control @ M	20.44	-.8
101941	Al Contacts	I	20.94	0
		T	21.04	+5.5
		H	20.93	0
		M	21.05	+5.5
101942	Al Contacts	I	19.78	0
		T	20.31	+2.7
		H	20.04	+1.3
		M	20.06	+1.4
101943	Al Contacts	I	20.38	0
		T	20.40	+1.1
		H	20.36	-.1
		M	20.45	+3.3
101944	Al Contacts	I	20.17	0
		T	20.56	+1.9
		H	20.24	+3.3
		M	20.32	+7.7

**TABLE 2**  
**ENVIRONMENTAL TEST RESULTS**  
**AG BACK CONTACT**

I.D. No.	Description	Test Point	P max (watts)	$\Delta$ P max (accumulated %)
101945	Ag Contacts	I	23.12	0
		T	23.05	-.3
		H	22.94	-.8
		M	22.83	-1.3
101946	Ag Contacts	I	22.66	0
		T	22.62	-.2
		H	22.51	-.7
		M	22.47	-.8
101947	Ag Contacts	I	22.63	0
		T	22.62	0
		H	22.48	-.7
		M	22.51	-.5
101948	Ag Contacts	I	22.52	0
		T	22.50	-.1
		H	22.35	-.8
		M	22.28	-1.1
101949	Ag Contacts	I	22.46	0
		T	22.41	-.2
		H	22.20	-1.6
		M	22.26	-1.0
101950	Ag Contacts	Control @ I	22.52	0
		Control @ T	22.49	-.1
		Control @ H	22.57	+.2
		Control @ M	22.73	+.9